# A Sensor Platform Capable of Aerial and Terrestrial Locomotion*

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***Abstract* – A sensor platform has been developed that is capable of both aerial and terrestrial locomotion, as well as transitioning between the two. The Morphing Micro Air-Land Vehicle (MMALV) implements biological inspiration in both flying and walking. MMALV integrates the University of Florida's Micro Air Vehicle (MAV) technology with the terrain mobility of Mini-Whegs™. Fabricated of lightweight carbon fiber, the UF-MAV employs a flexible wing design to achieve improved stability over other MAVs of similar size. Mini-Whegs™ employs the patented (pending) wheel-leg running gear that makes the Whegs™ and Mini-Whegs™ line of robots fast, agile, and efficient. MMALV has a 30.5cm wingspan, and is 25.4cm long. Terrestrial locomotion is achieved using two independently controlled wheel-legs, which are differentially actuated to perform turning. The vehicle successfully performs the transition from flight to walking. Furthermore, MMALV is capable of transitioning from terrestrial to aerial locomotion by walking off a structure of only 20 feet. A wing retraction mechanism improves the portability of the vehicle, as well as its terrestrial stealth and ability to enter small openings.**

***Index Terms – multi-mode mobility, micro air vehicle, Mini-Whegs™, morphing, reconnaissance***

## I. Introduction

Considerable interest has been generated in recent years in the area of ad hoc, reconfigurable sensor networks. The inherent redundancy of these networks makes them more robust to the loss of a single sensor. Similarly, by allowing the implementation of smaller sensor platforms, the stealth of the network is also enhanced. Sufficiently capable sensor networks could be used to locate weapons of mass destruction, perform reconnaissance for deployed military personnel and dramatically increase surveillance capabilities at major ports. Spatial reconfiguration of the sensor network will require mobile, semi-autonomous sensor platforms. This paper presents MMALV, the Morphing Micro Air-Land Vehicle. MMALV is a small, lightweight vehicle capable of both aerial and terrestrial locomotion. This dual-mode mobility significantly increases the vehicle's utility over other platforms for use in ad hoc, reconfigurable sensor networks.

MMALV was developed to improve near- and medium-field reconnaissance for ground based military personnel. To fulfill its proposed mission [1] MMALV must fly over 0.6km to a target zone and land on a building rooftop. Following completion of surveillance from the roofline perimeter, MMALV must take-off and return to the deployment zone. Fig. 1 depicts multiple stages of this scenario.


Fig. 1: In the proposed mission, MMALV must (a) fly up to 1.5km from the launch point to the target zone, (b) land on a rooftop within the target zone, and (c) walk to the edge of the building to survey the neighboring area.

To enhance stealth and be transportable by a single soldier, the platform should be small (wingspan < 30.5cm) and light (weight < 450g). To maximize indoor reconnaissance capabilities, it is also desirable that the vehicle be capable of reconfiguring upon landing, thus decreasing its overall dimensions.

The key to MMALV's success is the integration of the proven, highly adaptable UF-MAV and Mini-Whegs™

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technologies. Their lightweight, biologically inspired design makes them ideal for integration into a flying/walking vehicle.

The University of Florida's flexible wing design is the basis for MMALV's in flight capabilities. The flexible wing confers upon the UF-MAV several advantages over similarly sized rigid-wing vehicles [2]. Delayed stall allows the vehicle to operate at lower airspeeds and a higher angle of attack. Passive gust rejection significantly improves stability. The vehicle's carbon fiber construction is both lightweight and highly durable.

MMALV's terrestrial locomotion is based upon the Mini-Whegs™ line of robots, developed at Case Western Reserve University [3]. Several Mini-Whegs™ robots have been constructed, including models that are capable of jumping [4] and scaling vertical surfaces [5]. Mini-Whegs™ displays two characteristics critical to the successful field deployment of MMALV. Use of a single drive motor and diagonal gait coordination lead to a high level of efficiency, and the wheel-leg running gear provides Mini-Whegs™ with excellent terrain mobility.

## II. Background

### A. The Flexible Wing Micro Air Vehicle

It has been well established that the aerodynamic efficiency of conventional (smooth, rigid) airfoils is significantly compromised in the Reynolds number (Re) range between $10^4$ and $10^6$. This Re range corresponds to the class of craft referred to as micro air vehicles [6]. In fact, the ratio of coefficient of lift ($C_L$) to coefficient of drag ($C_D$) drops by nearly two orders of magnitude through this range. With smooth, rigid wings in this Re range, the laminar flow that prevails is easily separated, creating large separation bubbles, especially at higher angles of attack [7]. It is this flow separation that leads to sudden increases in drag, loss of efficiency and wing stall.

The effects of the relationship discussed above can also be observed in nature. Consider, for example, the behaviors of birds of various sizes. Large wingspan birds, which glide at $Re > 10^6$, tend to soar for prolonged periods of time. Medium-sized birds utilize a combination of flapping and gliding, while the smallest birds, which would soar at $Re < 10^4$, must flap continuously and rapidly to stay aloft.

Other major obstacles exist for flight on this scale [2]. Earth's atmosphere naturally exhibits turbulence with velocities on the same scale as the flight speed of MAVs. This can result in significant variations in airspeed from one wing to the other, which in turn leads to unwanted rolling and erratic flight. The small mass moments of inertia of these aircraft also adversely affect the stability and control characteristics of the vehicles. Even minor rolling or pitching moments can result in rapid movements that put the vehicle in orientations that are difficult to recover from.

Through the mechanism of passive adaptive washout, the flexible wing developed by the University of Florida overcomes many of the difficulties associated with flight on the micro air vehicle scale. Adaptive washout is a behavior of the wing that involves the shape of the wing passively changing to adapt to variations in airflow. For example, an airborne vehicle may encounter a turbulent headwind, such that the airspeed over only the right wing is suddenly increased. The compliant wing structure responds to the instantaneous lift generated by the gust to deform in a manner similar to Fig. 2. This is called adaptive washout, and results in a reduction in the apparent angle of attack, and a subsequent decrease in lifting efficiency, as compared to the left wing. However, because the air velocity over the right wing is higher, it continues to develop a nearly equivalent lifting force as the left wing. Similarly, as the airflow over the wing stabilizes, the wing returns to its original shape. This behavior results in a vehicle that exhibits exceptionally smooth flight, even in gusty conditions.

Fig. 2: Demonstrating the flexibility of the wing on the UF-MAV

### B. Terrestrial Locomotion

The real-world deployment of micro terrestrial robots has generally suffered from two primary shortcomings. The relative size of real-world obstacles makes navigation a daunting task for robots less than 45cm in size, and power-source miniaturization has lagged behind other critical technologies, such as actuation, sensing, and computation.

A wide array of vehicles have been constructed that attest to the difficulty of designing field-deployable mobile micro-robotics. Khepera robots have a 5cm wheelbase, onboard power, and considerable sensing capabilities [8]. However, their 1.4cm diameter wheels restrict them to operation on very smooth, flat surfaces. Millibots use tracks, but it is not clear that they offer much advantage because at this small scale it is difficult to implement a modern track suspension [9]. A small hexapod has been developed by Fukui et al. [10] that runs in a tripod gait using piezoelectric actuators. However, small joint excursions limit the vehicle to relatively flat surfaces. Birch et al. [11] developed a 7.5cm long hexapod inspired by the cricket and actuated by McKibben artificial muscles. It walks using 2 bars of air pressure, but the compressor is not onboard the vehicle.

The desired 30cm wingspan of MMALV could incorporate the terrestrial running gear of a larger robot than those described above. Sprawlita [12] is a 16cm long hexapod based upon the cockroach. Using a combination of servomotors and air cylinders, Sprawlita attains a top speed of 4.5 body lengths per second, which is fast compared to existing robots of similar size. However, operating at 6 bars of air pressure, it is unlikely that Sprawlita will ever be autonomous.

The implementation of biological locomotion principles holds considerable promise for terrestrial locomotion [13]. Legged animals exist and thrive at a wide range of sizes, and are capable of overcoming obstacles that are on the order of their own size. While direct biological inspiration tries to mimic the natural model to the greatest extent, this technique often requires new technology be developed in order to reach its full potential. Abstracted biological inspiration, on the other hand, attempts to abstract salient biological principles and implement them using available technology.

Locomotion studies of the cockroach illuminated several critical behaviors that endow the cockroach with its superior mobility [14]. During normal walking, the animal uses a tripod gait, where adjacent legs are 180° out of phase. The roach typically raises it front legs high in front of its body, allowing it to surmount smaller obstacle in stride. When climbing larger obstacles, the animal moves adjacent legs into phase, thus increasing stability.

The Whegs™ line of robots implement abstracted biological inspiration to reproduce the mobility behaviors outlined above [15]. Torsional compliance allows for a single motor to drive the six three-spoke wheel-leg appendages in such a manner as to accomplish all of the locomotion principles discussed above. The Whegs™ technology is also scalable, with successful robots being developed with body lengths ranging from 89cm down to only 9cm.

Mini-Whegs™ (Fig. 3) robots currently offer the best combination of speed, mobility, durability, autonomy, and payload. With a top speed of 10 body lengths per second, Mini-Whegs™ are significantly faster than most other legged robots [15]. The wheel-leg appendage results in a natural "high stepping" behavior, allowing the robot to surmount relatively large obstacles. The robots have tumbled down concrete stairs and been dropped from heights of over 10 body lengths, without damage. Mini-Whegs™ robots have also carried over twice their body weight in payload [17], ensuring that they will be able to support the UF-MAV airframe.

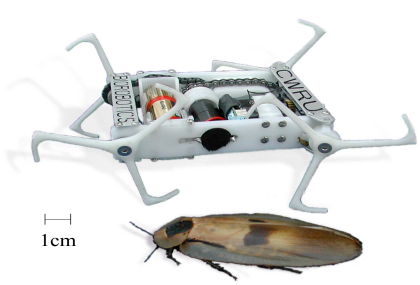


Fig. 3: Relative sizes of Mini-Whegs™ and *Blaberus giganticus* cockroach

## III. Vehicle Design and Fabrication

The payload capacity of the 30cm wingspan UF-MAV allows us to proceed in the most direct manner possible. The fuselage is modified as necessary to receive two servomotors near the front, with axes of rotation collinear, horizontal, and perpendicular to the fuselage axis. The servos are modified to allow for continual rotation, and each drives one wheel-leg appendage. This design requires the inclusion of a 5-channel R/C receiver (propeller motor, elevator, rudder, left wheel-leg, right wheel-leg), which is heavier than the 4-channel receiver previously used. The total mass associated with this implementation of terrestrial running gear is approximately 25g, which is confirmed to be within the payload capacity of the 30cm airframe.

Beginning with an estimated total vehicle weight of 120 grams and the established maximum dimension of 30 centimeters, a wing is designed that will provide the necessary flight characteristics for the vehicle. As the wing parameters (wingspan, root chord, sweep, ellipse ratio, curvature, etc.) are entered, the graphical user interface (Fig. 4) displays in real-time the top, side, and front projections of the wing. The program also outputs 2D aerodynamic estimates (coefficients of lift, moment, and drag and the lift to drag ratio) and key geometry features (planform area, aspect ratio and aerodynamic center). This provides the user with theoretical feedback concerning the performance of the wing design.

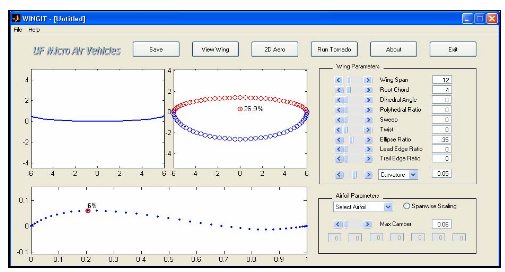


Fig. 4: User interface of the wing design software

Once a satisfactory wing design is reached, an output script file is generated. This script file is then imported into a CAD program (Fig. 5), where it is converted into CNC tool paths for milling the wing tool. The wing tool is a mold upon which the wing will be laid out during fabrication. The tool confers upon the wing the desired airfoil shape. The software scales and translates the airfoil shape so that the entire leading edge of the wing lies in a horizontal plane.

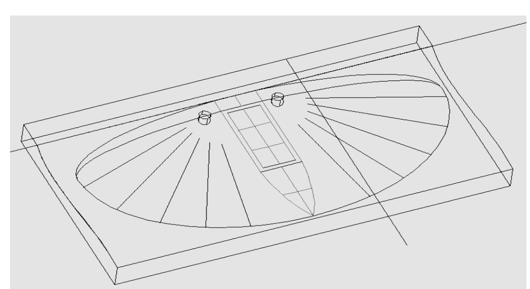

Fig. 5: A script file from the wing design software imported into CAD

After the wing tool is milled, it is prepared for the fabrication process [2]. First, a layer of release film is applied to prevent any resins or adhesives from bonding to and damaging the tool. A schematic of the wing layout (including the leading edge, ribs, and canopy) is then placed on the tool, and a second layer of release film is applied. Using unidirectional and plain weave resin-pregnated (prepreg) carbon fiber, the wing structure is laid out on the tool. The wing fabric, a polycarbonate-pregnated nylon, is then overlaid onto the structure. A final release film is applied, the tool is inserted into a vacuum bag, vacuum is applied, and the assembly is sent through an autoclave cure cycle.

The design of the fuselage is driven by location of the components. Component placement is determined by their weight and the desired center of gravity (CG) location. The more stable configuration is to have the CG forward of the wing's aerodynamic center. Previously, this was accomplished by placing most of the electronics in the nose of the aircraft. Because the wheel-leg drive servomotors are now consuming that space, the fuselage is extended to allow the electronics to be placed behind the motors, yet forward of the leading edge, thus maintaining the desired CG position.

With exception to how the fuselage tool is manufactured, the fuselage is fabricated in a manner similar to the wing. Instead of milling the fuselage tool, a top and side planform is generated using CAD software. These views are printed out and applied to a block of low-density foam. Using a band saw, the fuselage tool is rough cut from the block. The tool is then machined on a belt and disc sander to the desired shape. Examples of the fuselage tools, an array of wing fabrics and completed vehicles are pictured in Fig. 6.

Fig. 6: Three completed vehicles are shown with a series of fuselage tools and an array of investigated wing fabrics.

A tool is designed and fabricated that allows the wheel-leg motor horn to be molded into the wheel-leg (Fig. 7). The plastic horn, with splines that mate to the motor output shaft, is placed at the top of the "splaying cone". Their splayed shape allows the wheel-legs to reach out around (and in front of) the propeller, while minimizing the necessary width of the fuselage. Later tools included features that ensured the consistency of the spokes and "feet" of the wheel-leg.

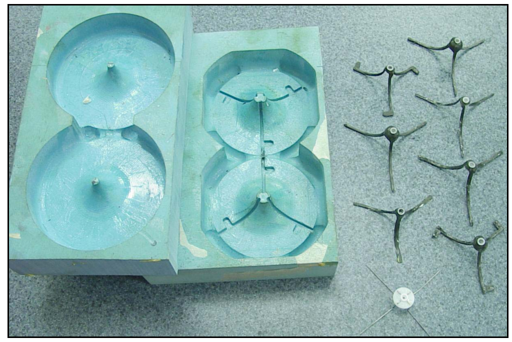

Fig. 7: Two CNC milled wheg tools and an array of tested wheg designs

## IV. Results

### A. *Multi-mode Locomotion*

The vehicle is capable of both aerial and terrestrial locomotion, as well as the transition from flight to walking under most circumstances. The flight characteristics of the vehicle are slightly compromised, as compared to a similarly designed MAV, due to high wing loading. Terrestrial locomotion capabilities diverge more significantly from the abilities of the component Mini-Whegs™ technology.

When the vehicle lands a significant load is placed on the wheel-legs and drive motors. Occasionally, the nylon hub that attaches the wheel-leg to the motor cracks under this load. This is the primary circumstance that prohibits transition from flight to walking. It was found that incorporating spring steel into the wheel-leg design helped absorb the high load at impact, thus reducing the likelihood of failure.

Multiple wheel-leg designs were evaluated against a variety of terrain and substrata. It was found that all designs were effective on semi-smooth concrete, dirt, and gravel. It was found that when the vehicle navigated through loose/fibrous materials, the wheg could become entangled, thereby stalling the drive motors. This difficulty was more pronounced for those wheel-legs that included "feet" (upper-left and lower-right wheel-legs in Fig. 7).

### B. *Rooftop Take-off*

The vehicle's ability to perform sufficiently at high angle-of-attack and low airspeed conditions resulted in a repeatable, successful take-off capability from atop a building structure. After the vehicle walks off of the roof of the structure, it enters a powered dive, pulled down by both gravity and the propeller. As airspeed builds, the necessary lift is generated to arrest the fall and transition to flight phase. Fig. 8 shows a sequence of frames from video of one successful take-off from a sloped rooftop.

Two primary modes of failure existed for performing rooftop take-off: 1) insufficient altitude to enter flight phase, and 2) inability to avoid obstacles in the immediate vicinity of the take-off point due to lack of control at low airspeeds.

Each of these modes of failure was found to have a direct correlation to the relative sideslip of the vehicle as it left the structure. Sideslip is a condition in which an aircraft's direction of motion is not coincident with the major axis of the fuselage. If the MMALV was able to leave the structure with little or no sideslip, the minimum height for consistent take-off was approximately 20ft, and the vehicle's path was nominally perpendicular to the building. Therefore, if the take-off location were sufficiently clear of obstacles, successful transition from rooftop walking to flight could be accomplished.

Fig. 8: a) MMALV nears the edge of the structure; b) MMALV walks off of the building, entering a "power dive"; c) lift is produced, and the vehicle pulls out of the dive

Two potential sources of sideslip were identified, both arising from the possible phasing of the two wheel-leg appendages. Just as the vehicle falls over the edge of the roof, if one wheel-leg is in a position to push off forcefully from the side of the building, but the other is not, a yawing motion will result. Similarly, if the wheel-legs are out of phase as the vehicle leaves the building one wing tip will be lower than the other. Both conditions result in a sideslip situation as the vehicle goes into the power dive phase of the take-off. Two things happen as a result of the sideslip: the downward acceleration is reduced, due to the oblique angle of the propeller thrust, and the vehicle deviates from its intended course. By the time the vehicle is reoriented, there may be insufficient altitude to pull out of the dive. Similarly, as the vehicle veers off course at low speed, there is insufficient controllability to avoid any impending obstacles.

Both failure modes are minimized by taking-off from a downward sloping surface. The vehicle is able to attain a higher ground speed on the inclined runway than on the flat surface, thereby reducing effect of wheel-leg phasing as the vehicle leaves the building. Therefore, the likelihood of significant yaw and/or wing dip, as well as the associated sideslip condition, is avoided.

### C. *Wing Reconfiguration*

A wing retraction system was developed to allow the vehicle to navigate more easily through complex obstacles. Fabricating the leading edge of the wing in two pieces, and pivoting each piece about an axis at the wings root allows for wing retraction.

By reducing the vehicle width from 30.5cm (12in) to 10.2cm (4in), the wing-retraction system allows the vehicle to enter through smaller openings. Fig. 9 shows a sequence of images, which demonstrate the vehicle's ability. The reconfiguration mechanism was insufficiently robust to attempt flight with the morphing prototype.

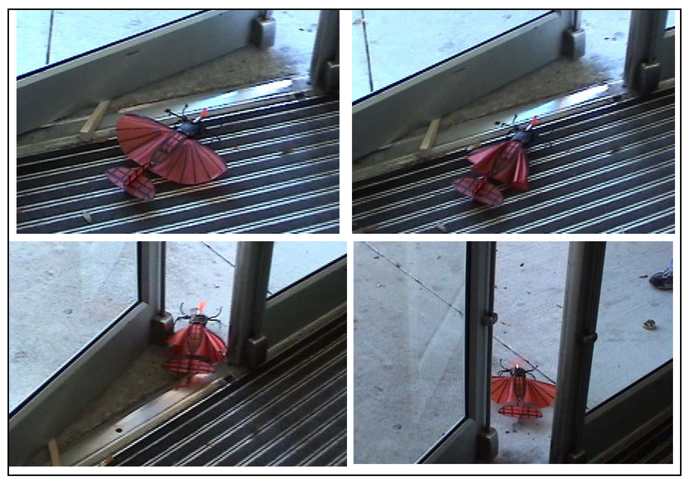

Fig. 9: When (a) MMALV is confronted with a narrow passage, it (b) retracts its wings, (c) negotiates the passage, and (d) redeploys its wings.

## V. DISCUSSION

We believe that all of the failure modes experienced for this prototype MMALV can be mitigated by implementing improvements to the terrestrial locomotion subsystem. The primary changes necessary to overcome most of the difficulties outlined in *IV - Results* are the addition of two rear wheel-legs and the implementation of a more robust drive train.

Regardless of the terrestrial drive motor used, a more robust drive train is imperative to withstand the impact loads encountered during landing. This capability is critical to the actual field deployment of MMALV. While spring-steel feet successfully circumvented the primary failure mode, the terrestrial performance of these feet is unacceptable for a field-deployed vehicle.

Rooftop take-off and general terrestrial mobility will be significantly enhanced by the addition of two wheel-legs at the rear of the vehicle. During rooftop take-off, the rear wheel-legs will provide impetus after the front wheel-legs are no longer in contact with the substrate. This will avoid the main source of sideslip during this procedure. Rear wheel-legs will also ensure that the vehicle is able to locomote backwards over obstacles.

In addition to these critical enhancements, several other design implementations would further improve the overall performance and field-ability of MMALV. Several iterations of wheel-leg running gear have been previously tested on the Mini-Whegs™ vehicles, and the preferred design is for each spoke to have a roughly teardrop shape. This was found to reduce the amount of snagging encountered on most substrates, as well as smoothen the body motions during walking.

As well as being an integral part of a robust drive train, a more powerful terrestrial drive motor would endow MMALV with more speed and more torque. The success of rooftop take-off from a slanted surface demonstrates that increased speed at take-off also helps to reduce the chances of failure.

The MMALV described here is operating near the limit of its flight capabilities under a remote operator and is approaching its maximum wing loading. While increasing the operating speed would increase the payload capacity, this occurs at the expense of efficiency. Two potential solutions present themselves to this problem: increased wing area and implementation of auto-stabilization hardware. Increasing the wing area will decrease wing loading and will increase the overall lift generated by the vehicle. Implementation of auto-stabilization routines will allow a remote pilot to operate MMALV at higher speeds, which would also result in increased lift. Using the additional lift to carry more batteries could overcome the decreased efficiency associated with operation at higher speeds.

## VI. Conclusions

It is a testament to the UF-MAV and Mini-Whegs™ technologies that the prototype described here attained this level of success. We expect the recommendations outlined in the previous section to fully address the failure modes experienced during testing, and generally enhance the performance and usability of MMALV.

## Acknowledgements

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